BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, L.I., N.Y.

ACCELERATOR DEPARTMENT
Internal Report

AGSCD-10

SHIELDING OF THE 200-MEV LINAC

G.W. Wheeler and W.H. Moore

May 18, 1966

The central problem in designing the shielding for the proposed 200-MeV linac injector for the AGS conversion program is that of estimating the number and distribution of protons lost in the linac during the acceleration process. The first part of this report concerns itself with establishing a rational and conservative set of criteria for beam loss in the linac. In the second part of the report, these criteria for beam loss are used to calculate the shielding requirements. In addition, consideration is given to the effect of penetrations in the shielding, to activation of the linac components, and to methods of control and monitoring of the radiation.

I. The Criteria for Beam Loss in the Linac

In principle, it is possible to design a linac which will capture and accelerate 100% of the injected beam, thus producing no nuclear radiation. This design has not yet been achieved in practice.

During the injection and capture process in existing linacs, as much as 50% of the injected beam may be lost but this loss occurs at such low energies that essentially no nuclear radiation is produced. The proposed 200-MeV linac will have a Cockcroft-Walton generator of 750 kV as its injector and will receive a peak current of 200 mA when accelerating 100 mA. Theoretical calculations and measurements on existing machines show that most of this loss will occur before the proton energy reaches 5 MeV, and all before 10 MeV. The lost protons will be stopped on the copper surfaces of the drift tubes and will produce some X-rays but no appreciable flux of neutrons. The first cavity of the 200-MeV linac is terminated at the 10-MeV point. Consequently, the radiation source arising from the Cockcroft-Walton, beam transport and first linac cavity will consist only of X-rays. This source will be supplemented to some extent by X-rays produced by the rf fields in the first cavity. The peak of this X-ray spectrum will be below 1 MeV.

The linac will consist of eight independent accelerating cavities. The second through eighth cavities will bring the proton energy from 10 MeV to 200 MeV and protons lost in these cavities will produce nuclear radiation. The processes which may lead to beam loss are the same for all of these cavities and they will be treated as a group. The total length of the accelerator from the 10-MeV point to the end (200-MeV point) is planned to be 450 feet.

Detailed theoretical calculations of beam dynamics and beam loading effects coupled with model measurements and experiments with existing linacs indicate that the 200-MeV linac can be operated with a total loss of 0.1% of the accelerated beam above 10 MeV. The shielding design originally proposed[1] for the linac is based on this assumption. However, to achieve the loss figure of 0.1% it will be required that the linac be perfectly tuned and all systems operating at optimum performance at all times.

Careful consideration of the operating requirements of the AGS complex show that it is desirable to allow the linac to operate under conditions less than optimum, that is, with more than 0.1% beam loss. The reason for this is clear: one wishes to minimize the linac downtime for tuning since the tuning operation would shut down the entire AGS complex. Thus it is much better to design extra shielding into the linac structure initially and permit the linac to run with somewhat higher beam losses. This philosophy is somewhat of a departure from that shown in the Scope of Phase I (BNL 9500), and is reflected in the shielding thickness shown in this report.

The mechanisms of beam loss in the linac above 10 MeV (Cavity No. 2 and beyond) are of two kinds: 1) loss of longitudinal stability, and 2) failure of the radial stability (focusing) system. In general, protons entering the

---

1. "Alternating-Gradient Synchrotron Conversion Program - Scope of Phase I," BNL 9500, September 1965.

second cavity of the linac are fairly well bunched* in the center of the longitudinal stability region and will be stably accelerated unless some disruptive force is introduced. These forces can arise from several causes:

a) Low accelerating field in the cavity.
b) Cavity operating off resonance.
c) Incorrect phase relation between cavities.
d) Transient phenomena due to beam loading.

In each of these cases, the result is to drive some of the protons outside of the boundary of the phase-stable region. Once outside the boundary, these protons fail to gain energy at the correct rate and become overfocused by the quadrupole lens system, and then move outward radially until they strike the bore of some drift tube where they interact.

The causes of loss listed in items a, b, and c occur only as "machine failures". Normally, these parameters are controlled during linac operation by servo systems which maintain the operation within limits which will not permit loss of particles.* When a loss does occur from one of these causes, the lost protons will be distributed over a distance of about 100 feet starting somewhat downstream from the point of loss of phase stability.

Item d, transient phenomena due to beam loading, is the major source of loss which will give rise to continuous loss during normal operation of the accelerator. This loss will be essentially uniformly distributed along the entire length of the accelerator above 10 MeV, and under the <u>ideal</u> conditions of linac tune-up should not exceed 0.1% of the total beam.

---

*Note: When using a conventional buncher, a small part of the beam (a fraction of 1%) may remain near the boundary of the phase-stable region as the beam enters the second cavity. Normal variation of the machine parameters within the limits set by the servo systems may cause a few of these peripheral particles to move outside the stable region and be lost. Several techniques exist for eliminating these peripheral particles before they enter the second cavity.

Loss of particles from the beam due to failure of the quadrupole focusing system is also clearly a "machine failure". Under these circumstances the beam will be lost in a distance of about 30 feet immediately downstream of the failure point.

A brief review of the linac operational characteristics is in order. The linac design calls for a peak beam current of 50 mA with the provision for increasing this to 100 mA. The shielding is designed on the basis of the ultimate use of 100 mA peak current for injection purposes. The beam pulse length is designed to be 200 μsec and a maximum repetition rate capability of 30 pulses per second is planned. The maximum pulse rate for injection into the AGS is set at 5 pps. At full AGS energy, the maximum injection rate will be 1 pps. However, one additional pulse per second will be used for injection monitoring and under some circumstances the AGS may be cycled faster at lower energies, hence the 5 pps maximum for injection service. At 50 mA peak linac current a pulse length up to 200 μsec may be required to reach 10^{13} protons accelerated in the AGS. Clearly, if the linac is operated at 100 mA peak, the injection pulse length will be reduced to 100 μsec (fewer turns) for 10^{13} protons accelerated in the AGS.

The possibility also exists that the linac may be used as a source of 200-MeV protons for parasitic experiments (particularly radio-chemistry and polarized protons), taking pulses between the AGS injection pulses. Thus about 25 pps can be made available for parasitic use. The peak current needed for parasitic use is about 10 mA at 200 μsec pulse length.

With this background, it is possible to set limits on the proton loss in the linac between 10 MeV and 200 MeV for the several operating modes. This is shown in Table I.

The allowed continuous loss of protons shown in Table I is substantially greater than the 0.1% loss which is asserted to be realizable. Clearly this arises from the necessity to be conservative. A large loss is to be allowed if necessary during the injection pulses in order that the AGS may be kept operating even when the linac is not well tuned. The choice of a 5% allowable loss is rather arbitrary, but conservative. Parasitic use of the beam is restricted to a loss of 0.5%, somewhat less stringent than the ideal 0.1% If the linac is not well enough tuned to achieve 0.5% loss, the parasitic use will have to be discontinued until the linac can be retuned. Since the beam loss is primarily a function of beam loading the 10 mA peak beam will be held to 0.5% loss more easily than the 100 mA beam. The last entry in Table I shows that the linac could, if desired, be operated at its maximum design ratings when well tuned up.

TABLE I

Beam Loss Above 10 MeV in the 200-MeV Linac

Service	Peak Beam Current (mA)	Beam Pulse Length (μsec)	Rep. Rate (pps)	Allowed Loss % of Peak	Protons Lost Per Second
Injection	50	200	5	5	
	or 100	100	5	5	1.56×10^{13}
Parasitic Use	10	200	25	0.5	0.16×10^{13}
				Total ~	1.8×10^{13}
or					
Maximum Capability	100	200	30	0.5	$\sim 1.8 \times 10^{13}$

Thus the design criterion is a continuous loss of beam during operation amounting to 1.8×10^{13} protons per second uniformly distributed as a line source from 10 MeV to 200 MeV along the linac center line. The distance involved is 450 ft so there will be 4×10^{10} protons/ft/sec. In the shielding calculations this source will be treated as an infinite line source.

For the case of protons lost due to "machine failure", consider the worst case which is quadrupole magnet failure, because then the beam is lost over a shorter distance (about 30 ft) than with other kinds of failure. When a machine failure occurs, it will be detected by one of several protective circuits (see subsequent sections of this report), which will stop all beam within 20 μsec of the onset of a failure. The failure will then contribute (in the worst case) 100 mA for 20 μsec over a distance of 30 ft which constitutes a source of 4.2×10^{11} protons/ft. If such a failure were allowed to occur once per minute, this would add 0.7×10^{10} protons/ft/sec to the continuous background or an increase in the level of 17% locally in the area of the failure. If such a failure occurs once per minute for a period exceeding a few minutes, corrective maintenance of the linac is in order.

The worst situation which could arise and is classed a catastrophic accident would be to spill the entire beam over a short distance (30 ft length), that is, a loss of 100 mA, 200 μsec pulse length at 30 pps until the linac destroyed itself.* Such a catastrophe could only occur if all of the protective and warning circuits failed simultaneously (the probability is less than 1 in 10^4 per day of operation) and if the operators failed to notice that something was wrong. With this kind of spill, the linac would certainly destroy itself in less than 5 minutes. This would be a source of about 10^{18} protons over 30 ft or about 1.33×10^{14} protons/ft/sec for 5 minutes. Recalling that the shield is designed for a continuous loss of 4×10^{10} protons/ft/sec (an infinite line source) to yield a tolerable level (2.5 mrem/hr) outside of the shield, it is evident that a spill of the entire beam for 5 minutes would deliver about 0.7 rem locally outside the shield.

It is evident that a shield thickness designed to reduce the radiation levels to or below 2.5 mrem/hr outside the shield for a continuous loss of 1.8×10^{13} protons/sec will be adequate for any foreseeable types of machine failure.

---

*Note: At 150 MeV, for example, the heat generated by the beam in stopping is 90 kW. This amount of heat deposited in the drift tube bores over about 30 ft will quickly raise the temperature of the drift tubes to destructive levels. Gas evolved from the surfaces will cause sparking in the cavity and then complete loss of rf power in the cavity. Intense local heating of the surfaces by the beam will melt the metal of the drift tube bores and damage the quadrupole windings.

II. Design of the Shielding

The shielding thickness is calculated on the basis of a continuous loss of 1.8×10^{13} protons/sec uniformly distributed over a distance of 450 ft (1.37×10^4 cm) from the end of Cavity No. 1 (10 MeV) to the end of Cavity No. 8 (200 MeV). The treatment follows the calculations of Reference 2. The source is considered to be the cascade neutrons arising from protons stopping in the copper of the accelerator. Because of their lower energy, the evaporation neutrons are not considered although the number of evaporation neutrons produced will be comparable to the number of cascade neutrons. No allowance is made for the absorption of neutrons by the copper and steel of the accelerator itself.

From Reference 2, p. IV-88, a 200-MeV proton stopping in copper will produce 0.2 cascade neutrons on the average. In general, these neutrons will have a $\gamma < 1.1$ and from Fig. B-4 (Y-12-IV-92) it is reasonable to assume an approximately isotropic angular distribution. It is assumed that the neutron source strength decreases linearly to zero with decreasing proton energy. Thus the source strength can be written:

$$S = \frac{0.2\ P}{T_o} (a + bz) \quad \text{neutrons/cm/sec} \ ,$$

where

P = number of protons stopping (lost from the beam)/cm/sec

a,b, are constants

z = the distance along the linac in centimeters, measured from the end of Cavity No. 1

T_o = proton energy which yields 0.2 cascade neutrons per stopping proton, 200 MeV.

2. Yale University Internal Report Y-12, October 1964.

Now, at $z = 0$, $T = 10$ MeV and at $z = 1.37 \times 10^4$ cm (450 ft) $T = T_o = 200$ MeV, so that $a = 10$ MeV, $b = 1.38 \times 10^{-2}$ MeV/cm. Thus, $S = 10^{-3}\, P\, (10 + 1.38 \times 10^{-2}\, z)$ neutrons/cm/sec. Since

$$P = \frac{1.8 \times 10^{13} \text{ protons/sec}}{1.37 \times 10^4 \text{ cm}} = 1.31 \times 10^9 \text{ protons/cm/sec}$$

$$S = 1.31 \times 10^6\, (10 + 1.38 \times 10^{-2}\, z) \text{ n/cm/sec} . \qquad (1)$$

The shortest distance from the accelerator center line to the inside wall of the linac tunnel is $R_o = 7$ ft or 214 cm. Assuming that the source is an infinite line source, the neutron flux at the wall will be

$$I(z) = \frac{2S}{R_o}$$

or

$$I(z) = 1.22 \times 10^4\, (10 + 1.38 \times 10^{-2}\, z) \text{ neutrons/cm}^2\text{/sec} .$$

The neutron flux outside the shield should be such that the dose rate is within tolerance for a 40-hour work week, or 2.5 mrem/hr. A conservative criterion is 2.5 mrem/hr $\approx$ 17 neutrons/cm^2/sec. Thus

$$I(z)\, e^{-X(z)/\lambda(z)} = 17 \text{ n/cm}^2\text{/sec}$$

where X is the shield thickness at length z and $\lambda(z)$ is the attenuation length for neutrons in the shield material and increases with z because the neutron energy is increasing. The functions I(z) and $\lambda(z)$ are plotted in Figure 1. It is assumed that the average cascade neutron energy is one half of the incident proton energy, and the values for $\lambda(z)$ are taken from Fig. C-1 (Y-12-IV-96) (which shows the half thickness) and are those appropriate for ordinary concrete.

Finally,

$$X(z) = \lambda(z)\, \ell n \left(\frac{I(z)}{17} \right) . \qquad (2)$$

Equation (2) is plotted in Figure 2. It is believed that the assumptions and calculations leading to the results in Fig. 2 are sufficiently conservative to assure a safe installation for all expected conditions of operation. It should be noted that an error of a factor of 10 in I(z) changes the shielding thickness at 200 MeV by only 2.6 ft of concrete or about 4 ft of sand.

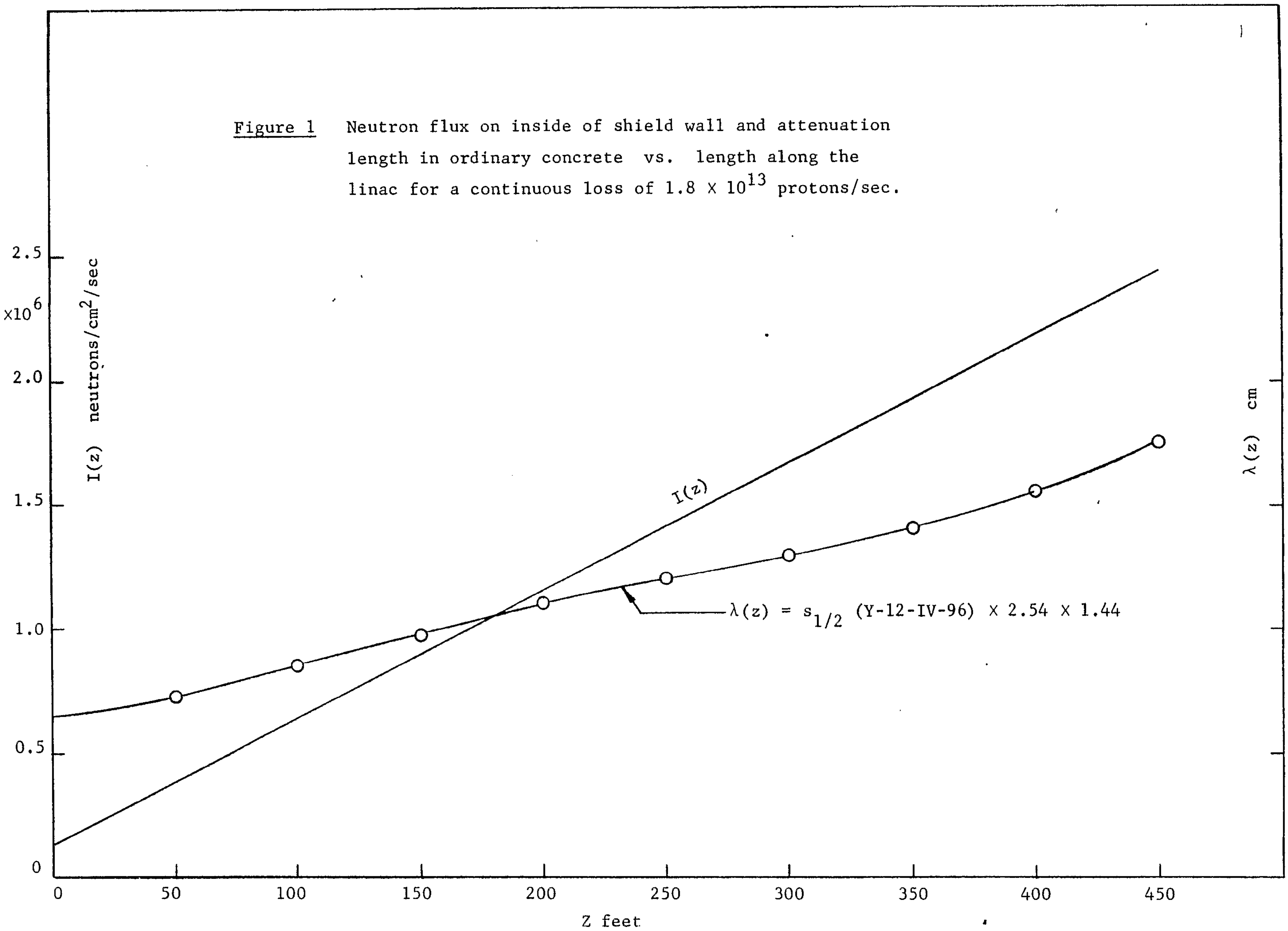


Figure 1 Neutron flux on inside of shield wall and attenuation length in ordinary concrete vs. length along the linac for a continuous loss of 1.8×10^{13} protons/sec.

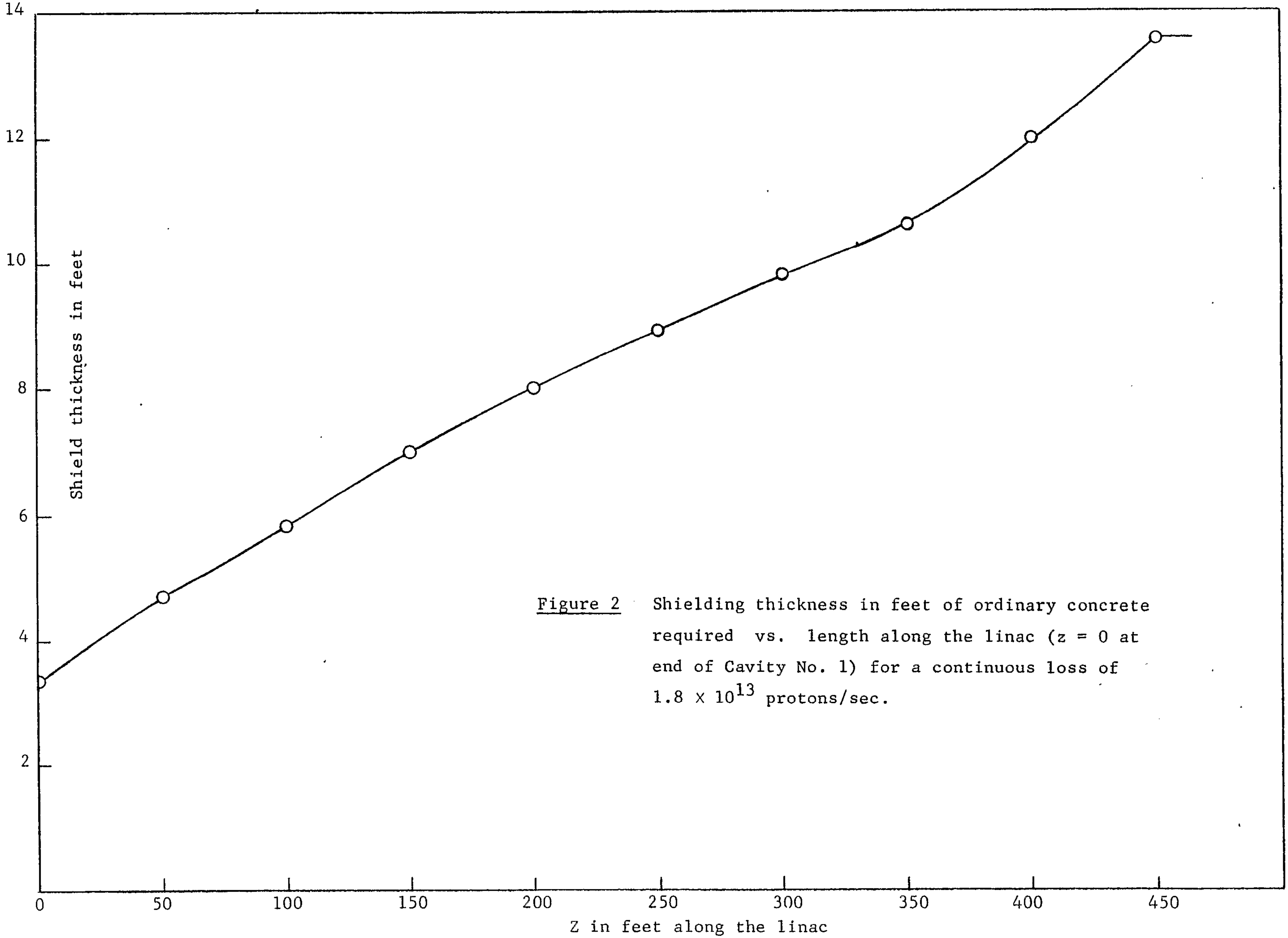


Figure 2 Shielding thickness in feet of ordinary concrete required vs. length along the linac (z = 0 at end of Cavity No. 1) for a continuous loss of 1.8×10^{13} protons/sec.

The layout of the buildings as presently planned in order to achieve the shielding as indicated in Fig. 2, is shown on the attached drawing D20-OA-29-4. If more economical alternatives for achieving the required shielding thickness are found during the design, these alternatives will be incorporated into the building design. The linac is located in a concrete tunnel 16 ft wide by 15 ft high. The walls are made of ordinary (150 lb/ft^3) reinforced concrete, averaging 20 inches in thickness. On one side (west) and on top the rest of the shielding is supplied by local sand (density 100 lb/ft^3). At the 200-MeV point the sand above the tunnel will be 18 ft thick and will taper gradually to 3 ft at the 10-MeV point and will remain at this depth up to the point where the linac tunnel joins the preinjector building. The tunnel walls, roof and footings will be strong enough so that additional sand can be added later if it should become necessary.

The two-story equipment bay which houses the equipment associated with the linac runs parallel to the linac on the east side of the tunnel. The west wall of this building is made of 18 to 24 inch thick reinforced concrete. The separation of the bay and the tunnel is determined by the shielding thickness required at 200 MeV, i.e., 13.6 ft of concrete equivalent. Thus, at the 200-MeV point, two 24 inch concrete walls and 15 ft of sand make up the shield. There is considerable advantage in simplicity of construction to be gained at small increase in cost by making the tunnel and the equipment bay parallel, even though this means that the lower energy part of the linac is much over-shielded. If it should become necessary at a later time to increase the amount of shielding at the 200-MeV region, this can be readily done by removing the sand between the two structures and filling the region with poured concrete.

The shielding of the preinjector units is accomplished by enclosing them in rooms which have 12 inch thick reinforced concrete walls and roof which will attenuate the X-ray background by a factor of 100. If more attenuation is needed, it is a straightforward matter to face the walls with a thin lead sheet. The beam transport area from the preinjectors to the first linac cavity will be enclosed by 18 in. to 24 in. thick concrete walls, either cast in place or erected of block, depending on the need for access during construction.

Although there will be no neutron production below 10 MeV, some of the neutron flux from the linac tunnel will diffuse back toward the low energy end.

This flux will be contained by a movable concrete block shield wall erected across the tunnel in the vicinity of Cavity No. 1. The thickness and location of this wall will be adjusted as necessary.

From the 200-MeV end of the linac, the beam will be transported about 50 ft by a quadrupole system to a fast switching magnet located in an extension to the linac tunnel. From this point the beam may be switched 90° to the east to go to the future parasitic experimental area, may proceed straight down the injection tunnel, or may be switched 30° to the west into a beam analysis area.

Under normal circumstances, there should be no loss of beam in the switching magnet nor in the transport system. Under fault conditions, proton losses similar to those listed under "machine failures" on p. 5 could occur. A conservative shield will be provided by carrying the 18 ft of sand cover from the 200-MeV point over the switching magnet.

The beam quality from the linac will be continuously monitored during operation. Normally one pulse per second will be deflected in the beam analysis area although on occasion as many as 5 pps might be used. After deflection into the analysis area by the switching magnet, the beam will be passed through equipment which will measure emittance, energy, energy spread, etc. The beam will then be transported to a heavily shielded beam dump located at the end of the tunnel. There will be some loss of beam in the analysis process but most of the beam will be absorbed in the dump. The shielding required for dumping the full beam (100 mA peak, 200 μsec pulse length, 30 pps) has been calculated to be 27 ft of sand. Since less than 10% of this beam will ever be dumped, the shielding plan calls for 20 ft of sand cover initially with the ability to put the 27 ft of sand cover over the beam dump if it should ever be necessary.

The injection tunnel beyond the switching magnet will be 10 ft × 10 ft and run straight for about 205 ft to a first deflecting magnet which bends the beam 17.5° to the west. The beam then travels 100 ft to a second 17.5° deflecting magnet which sends the beam to the inflector. Throughout this run, the beam is contained by a quadrupole lens system. Beam can only be lost from this system by failure of one of the magnets. Any maladjustment of this transport system will be immediately detected by the inability to inject beam into the AGS. By arguments similar to those used for establishing the average losses in the linac (but somewhat less clear-cut), a time average loss of protons from all causes in any 10 m section of the injection tunnel is set at 10^{10} protons/sec at 200-MeV energy. This will require 10 ft of sand cover on the tunnel. It is to be noted that the area above the tunnel will never be occupied regularly. Provision for adding more fill over the tunnel is built into the tunnel walls and footings.

III. Penetrations

All of the services for the linac will enter and leave the linac tunnel via horizontal penetrations in the shield wall between the tunnel and the equipment bay. The following penetrations will be needed:

1) Fifteen 18 in. diameter pipes for the coaxial rf feed lines. There will be two feeds to each cavity except Cavity No. 1 which has only one feed.

2) Twenty 2 ft × 2 ft ducts for piping and cables, roughly uniformly spaced along the linac.

3) Several air ducts, 18 in. × 48 in. maximum.

The ducts for items 1 and 2 must be straight through the shield in order to allow installation and removal of the pipes and cables. The ducts will be at floor level so that they do not look directly at the neutron source. Where the services leave the ducts to enter the equipment bay, all services will bend up 90° and be carried up the wall for a distance of 6 ft to 10 ft. A removable concrete block "chimney" of about 5 ft thickness will surround each duct to a height of 6 ft. Because of the uniform shield wall thickness and the decreasing neutron flux at lower energies, calculations on the leakage through these ducts will be given only for the 200-MeV end of the linac.

The air ducts (item 3), since they carry only air, will have multiple bends built into them in the shield wall. They will be located between the middle and low energy end of the linac tunnel. The multiple bends will result in locally thinning the shield wall by about 4 ft of sand or less, but at the middle of the tunnel, the shield wall is more than 4 ft thicker than necessary. The air will be exhausted from the tunnel near the switching magnet and near the AGS end of the injection tunnel. The exhaust ducts will penetrate the top of the shielding with multiple bends and will vent to the outside.

The exact calculation of neutron leakage through ducts is difficult and uncertain. However, some estimates can be made. Following the treatment of Ref. 2 (p. IV-104), which is based on information from reactor and accelerator installations, the leakage of fast neutrons through two of the ducts at the 200-MeV point will be examined. The fast neutron flux at the inside of the shield wall directly opposite the beam center line was shown to be 2.4×10^6 neutrons/cm^2/sec. At the entrance to the duct at floor level, the flux will be somewhat lower. The thermal neutron flux in the tunnel will be considerably lower than the fast flux, probably by a factor of 10 or more. Additional attenuation of the thermal neutrons in the ducts can be achieved by lining the ducts with material rich in Boron (or Cadmium) which strongly absorbs thermal neutrons.

Equation D-1 of Ref. 2 (p. IV-104) gives the attenuation in a straight duct:

$$g = \frac{1}{4}\left(\frac{a}{Z}\right)^2 \left(1 + K\frac{a}{Z}\right)$$

where

a = radius of a circular duct
Z = length of duct
K = constant, $\sim$ 16 for fast neutrons
$\sim$ 60 for thermal neutrons.

The total shield wall thickness is 19 ft and the radius of the duct for the coaxial line is 0.75 ft. Thus $g_1 = 6.3 \times 10^{-4}$ for fast neutrons and 13×10^{-4} for thermals. For the 6 ft high vertical duct formed by the concrete blocks stacked at the end of the pipe, Z = 6 ft and a $\cong$ 0.84 (the equivalent radius for a square duct 18 in. $\times$ 18 in.). Thus the attenuation $g_2 = 1.6 \times 10^{-2}$ for fast neutrons and 4.6×10^{-2} for thermal neutrons. From Eq. D-2 of Ref. 2 (p. IV-105), the total attenuation is:

$$g_t = g_1\, g_2\, \frac{c}{\sin\theta}$$

where c is a constant ~ 1/3 for thermal neutrons and smaller for fast neutrons and θ is the angle of the bend, here 90°. This expression underestimates the attenuation for a 90° bend. However, using this expression should be conservative. Thus, the total attenuation through this combination will be about 3.4×10^{-6} for fast neutrons and 2×10^{-5} for thermals. For a fast flux of 2.4×10^{6} neutrons/cm^2/sec at 200 MeV, the flux escaping from this duct system will be about 8 neutrons/cm^2/sec.

It is not significant to make a similar calculation for the 2 ft x 2 ft cable and pipe ducts because they will be filled with heavy material. It is anticipated that 50% of the cross section of the duct will be occupied by wires, cable trays and pipes, all of which act as shielding material. Furthermore, after installation, any unused space in the duct will be packed with concrete or paraffin blocks. Therefore, it seems reasonable to conclude that there will be less leakage through the 2 ft x 2 ft ducts than through the 18 inch diameter ducts which carry the coaxial transmission lines (these lines have air dielectric and so offer little material for neutron attenuation).

Access to the tunnel will be provided at each end of the linac. At the low energy end, shielded doors will be provided in the concrete walls surrounding the beam transport area. At the high energy end of the linac, access to the tunnel will be through a plug door leading into the section of tunnel which will eventually supply the parasitic experimental area. The shielding between this side tunnel and the end of the equipment bay does not need to be as thick as the main shield because this tunnel will not be exposed to the high direct neutron flux which exists in the linac tunnel. The wall will consist of 4 ft of concrete and 8 ft of sand fill. The shielded access door will be composed of Ilmenite concrete (250 lb/cu.ft), 5 ft in thickness. During construction two straight through openings will be left in the wall between the linac tunnel and the equipment bay. These will be solidly plugged with concrete before the linac is operated.

IV. Activation of the Accelerator Components

In the calculations of shielding requirements, a continuous loss of 4×10^{10} protons/sec per foot of the accelerator was used. This loss of particles will cause activation of some of the accelerator components which may have to be handled from time to time. The protons lost from the beam strike the drift tube bores predominantly, although a small fraction of them will interact in the beam pipes which connect the cavities. Thus, by far the most severe activation will occur in the drift tubes themselves. In Ref. 2 (p. IV-23 and Fig. IV-5), the total activation and dose rates produced by a line source of 200-MeV protons is calculated. The lost proton intensity used is 2×10^{10} protons/sec/ft. Figure IV-5 of Ref. 2 may then be used for the high energy end of the 200-MeV linac by multiplying the ordinate of Fig. IV-5 by two. This indicates a field of about 80 mR/hr at 1 meter from the center line but does not include the shielding effect of the steel cavity walls, which will appreciably reduce this value. Thus it appears that there will be no serious problems for routine maintenance and repair activities. Levels of the order of 50 mR/hr are routinely encountered now around the AGS and routine maintenance is carried out without difficulty. Fields somewhat higher than 80 mR/hr will be encountered at the surface of the beam pipes connecting the cavities. These sections can be readily removed when necessary and replaced with fresh sections.

The worst problem which will be encountered in the linac is the removal of a drift tube or a general realignment of the drift tubes in the high energy cavities (Cavities No. 7 and No. 8, which contain about 24 drift tubes each). Fields in the drift tube bores, where most of the lost protons interact, may reach about 800 mR/hr. A major design effort is being aimed at a drift tube design which will permit installation, removal and alignment of the drift tubes without the necessity of having a man work inside the cavity. In any event, the time required for a man inside the cavity will be minimized.

Similar activation levels will be encountered in the immediate vicinity of the beam dump in the beam analysis area. The beam dump will be a very simple device requiring little maintenance and should present no problems.

All of the equipment which is exposed to activation will be constructed with the maximum use of radiation resistant materials to minimize maintenance and repair. The designs will be such as to minimize the time required when repair or replacement is necessary. For storage and repair of activated components, Brookhaven maintains hot storage areas and has a special "hot materials" shop which is equipped with special tools and specially trained personnel.

V. Monitoring and Control

Refined and effective radiation monitoring and control procedures[3] already exist at the Brookhaven AGS. These procedures will be expanded to include the 200-MeV linac.

All personnel will be excluded from the following areas while the linac is operating: the pit containing the preinjector which is in operation, the beam transport area from preinjector to linac, the linac tunnel, the injection tunnel to the AGS, and the beam analysis and beam stop area. The following areas may be radiation areas requiring all personnel to wear film badges: the linac service building and assembly area, the equipment bay (both floors), and the earth-covered areas above the linac tunnel, injection tunnel and the beam analysis area (these earth-covered areas will be fenced off if this is shown to be necessary).

Three general systems will be integrated into the linac control system to assure that excessive amounts of linac beam are not lost. Any one of these three systems will shut down the linac beam within 20 μsec of the start of a fault. A fault is defined as any situation which causes a local or general loss of beam in excess of the amount stated earlier in this report. All of the machine parameters which affect the stability of the beam (rf field levels, intercavity phase, quadrupole magnet current, etc.) will be continuously monitored. Any departure from predetermined limits will shut down the beam and alert the operators. The beam current will be continuously monitored at regular intervals along the linac. Comparison between these monitors will show any beam loss and will shut down the beam. Finally, nuclear radiation detectors will be located at about 30 ft intervals along the linac tunnel and at appropriate points in the injection tunnel and in the beam analysis area. If any of these detectors indicate an increase in the radiation level above a preset value, the beam will be shut down.

---

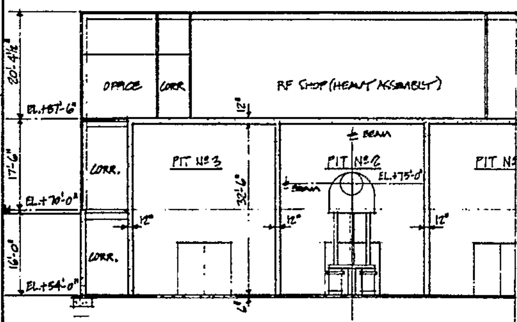
3. R.R. Kassner and W. Livant, Proc. IEEE Trans. Nucl. Sci. NS-12, June 1965, p. 689.

In addition to these monitors which are directly tied into the accelerator control system, there will be radiation detectors (both rate meters and integrating devices) located at frequent intervals in the equipment bay and in the linac service building.

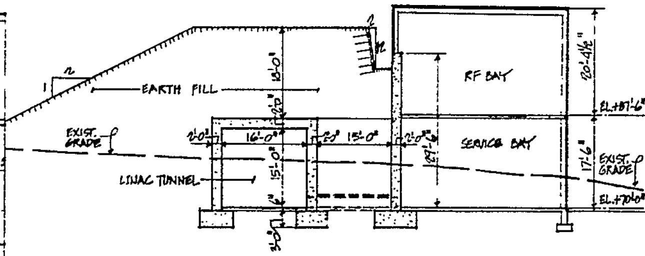
Access to the excluded areas will be controlled by keys and interlocks on all access doors. Standard personnel accounting procedures will be used. Machine status lights, crash buttons, voice systems and television monitoring will be included in all appropriate areas.

GWW/WHM:yew
5/19/66
Distr.: AGSCD External

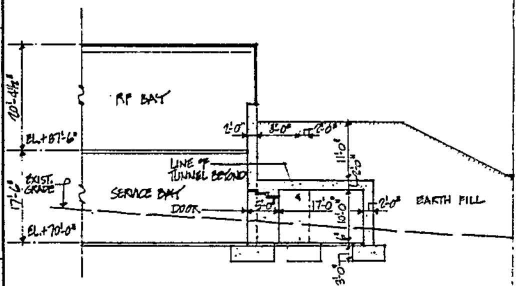
AGSCD-10



CROSS SECTION "A-A"



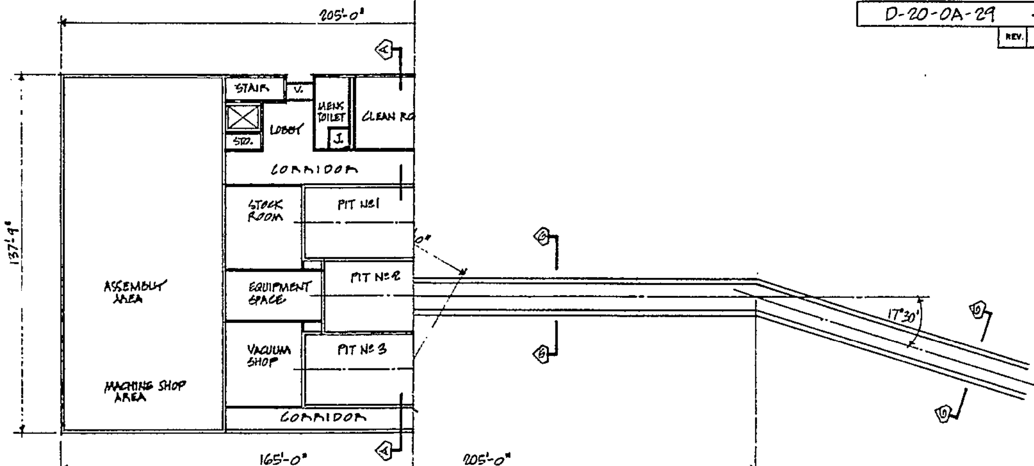
CROSS SECTION "D-D"



CROSS SECTION "E-E"

D-20-0A-29 -4

REV.



TOLERANCES — DECIMAL ±.005; FRACTIONAL (0-20") ±1/64; (20"-60") ±1/32; (OVER 60") ±1/16; ANGULAR — ±1/2°
CONCENTRICITY — WITHIN TOLERANCE OF DIAMETRAL DIM. ABOUT AXIS OF SMALLEST TOLERANCE CIRCLE;
FINISH—125 MICROINCH MAX; SQUARENESS—.002"/INCH; FLATNESS—PEAK TO VALLEY .002" WAVINESS—.001"/INCH
MAX; THREADS—UNIFIED SYSTEM CLASS 2; BREAK SHARP EDGES 1/64

ITEM NO	USED ON DWG. NO.	NO. REQD.

SHOP	I L R NO.	ACCT. NO.	W. O. NUMBER

MATERIAL SPEC.	SIZE	WEIGHT	SCALE
			1" = 30'-0"

DATE	DRAWN BY	CHECKED BY	APPROVED BY	JOB NUMBER
5-17-66	WJS			D-20-0A-

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, N. Y.

AGS-CONVERSION - 200 MeV
LINAC TUNNEL & SERVICE BAY PLAN
CROSS SECTIONS THRU LINAC TUNNEL

DRAWING NUMBER	REV.
D20-0A-29	-4

REV.	DESCRIPTION	BY	DATE	CKD

FORM NO. 100

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, L.I., N.Y.

AGSCD-10E

ACCELERATOR DEPARTMENT
Internal Report

SHIELDING OF THE 200-MEV LINAC

Erratum

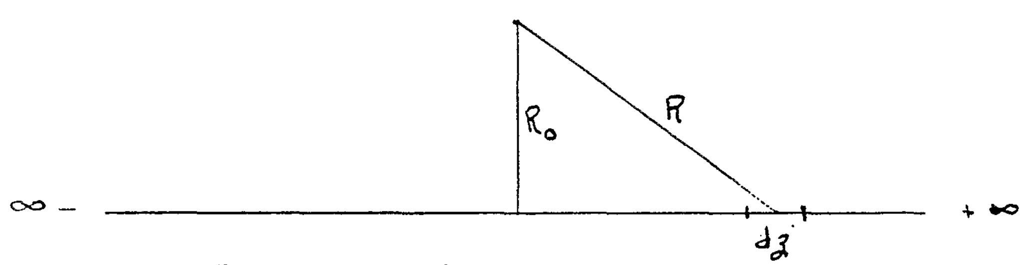
G.W. Wheeler and W.H. Moore

June 3, 1966

On page 8 of this report there is an error in the expression for the neutron flux at the inside of the shield wall (I_z). On the assumption of an infinite line source, it is stated that

$$I_z = \frac{2S}{R_o}$$

The correct expression is given below, see figure.



$$I_z = \int_{-\infty}^{\infty} \frac{Sdz}{4\pi R^2} = \frac{S}{4\pi} \int_{-\infty}^{\infty} \frac{dz}{R_o^2 + z^2} = \frac{S}{4R_o} , \qquad \text{(A)}$$

where the value of S used is that appropriate to the length, z.

Thus, the values of I_z used in the report are high by a factor of 8. At either end of the linac, Eq. (A) still overestimates the flux by a factor of 2 because the source becomes a semi-infinite source (the integration is carried from 0 to ∞). However, this overestimate is compensated at the high energy end of the linac by the fact that the neutron production is not in fact isotropic as assumed, but is peaked in the forward direction by about a factor of 2 (Report Y-12 pIV-92, Fig. B-4).

A detailed analysis which includes the effect of the variation of S with z and the finite length of the linac leads to results which are within a factor of two of these given by Eq. (A).

The fact that the flux on the inner wall of the shield is not all perpendicular to it is not included in the calculation nor is the 1/R attenuation in the shield itself. Both of these factors will further reduce the flux at the outside of the shield.

The overestimate by a factor of 8 amounts to almost 4 feet of sand thickness and it is recommended that the shield wall thickness be reduced by this amount.